NISTIR 6327

Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete

Report from the NIST/ACI/ASTM Workshop held in Gaithersburg, MD on November 9-10, 1998

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at other places with the appropriate combination of sufficiently high potential and chloride contamination. Every time an additional spot becomes active, the potential distribution becomes readjusted and so does the C_T distribution. As each spot enters the active corrosion condition, the corrosion distribution module calculates the local corrosion rate. The rate is integrated as a function of time and converted into local corrosion penetration with a value M_{crit} assumed to result in concrete cover spalling for the combination of steel (rebar) diameter and concrete cover used at that location of the system. When M_{crit} is reached at a given element of the system, the element is declared damaged and its projected area on the external concrete surface counted as damaged area. The sum of damaged area for the entire system as a function of time is defined as the *damage function* of the system.

2.3 PRESENT LIMITATIONS IN SCIENTIFICALLY-BASED PREDICTION MODELS FOR CHLORIDE INGRESS INTO SUBMERGED CONCRETE

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Most current prediction models for chloride ingress into concrete are empirical and depend on fitting curves to measured chloride profiles. Since the models do not have firm physical and chemical foundations, predictions are made by extrapolation from existing data. The results of the extrapolations are uncertain because of large scatter in the data and uncertainties in the models. Chalmers University of Technology has developed scientifically-based models that use current knowledge of the physical and chemical processes involved in the transport of chlorides in concrete. They have concentrated mostly on chloride ingress and a little on the corrosion threshold. They have used a lot of literature data, some from people at the present workshop. The model runs in a WINDOWS environment.

This study described [5] had the objective of determining the possibilities and the limits of the Chalmers University (CTH) model for predicting the penetration of chloride ions into concrete. The diffusion of chloride is established from Fick's first law and a diffusion coefficient is determined by the CTH Migration Test. The effects of temperature, age of the concrete, and the variation of the diffusion coefficient as a function of depth have been examined. The interactions between chlorides and the concrete are represented as a function of concentration of free chloride, temperature, and pH of the pore solution. Leaching of alkalis is included in the model to predict the pH at different depths.

The results of the predictions for different cases have been compared with results of measurements made in the laboratory and the field. Differences between predictions and the results of accelerated immersion tests at elevated temperatures appear to be due to the fact that the diffusion coefficient depends on concentration. The effect of unsaturation of the submerged concrete is illustrated by some examples and its consequences are analyzed.

Predictive models that are described as "scientific" should be based on relevant and decisive physical and chemical parameters such as mass balance equations, a genuine flux equation, chloride binding relationships, the effect of material characteristics, and the effect of environmental conditions. Such a model, ***ClinConc***, has been developed by Tang [6]. Features of the model are:

- non-linear binding isotherms, $c_b(c, T, [OH^-])$, including the significant effects of both pH and temperature;
- a chloride diffusion equation with free chloride concentration as the driving potential,
- a chloride diffusion coefficient, D_{CTH} (t, T, X), that is a function of age, temperature, distance to the cast surface, etc.;
- a method for measuring the chloride diffusion coefficient, D_{CTH} , in an independent chloride migration test; and
- leaching of alkali hydroxides by a separate mass balance equation.

The model predicts total and free chloride distributions and the distribution of hydroxides. Comparison with measured chloride profiles has shown that, with but a few exceptions, predictions made with the model are accurate. The exceptions are:

- the predicted penetration is too high when compared with that measured after exposure to the Scandinavian NT Build 443 immersion test [7]; in this test, the chloride concentration is much higher than in normal exposures;
- the effect of unsaturated pores has not yet been considered in a completely correct way; a number of measurements have shown that good concrete is far from saturated in the submerged zone, even after long exposure times;
- the effect of temperature on chloride binding is still unclear; experimental results do not agree with theory, and this causes a large uncertainty; (in summer, temperature effects cause increases in the free Cl^- concentration);
- the effect of temperature on the diffusion coefficient is also uncertain, since data on the steady-state diffusion coefficient are rare; and
- predicted chloride contents close to the exposed surface are somewhat low in some cases; a number of surface effects that could influence binding have not been considered.

It is concluded that the ***ClinConc*** model for chloride penetration is very promising for predicting actual chloride profiles in submerged parts of structures. The demands for input data are small and short-term tests can provide the data. The inputs include mixture proportions, workmanship, and exposure conditions, and the only parameter to be measured is D_{CTH} . This can be obtained from a simple test using silver nitrate applied to a split concrete sample. A good rapid test for chloride diffusion is needed, but the AASHTO test is not suitable.

The predicted results are meant to be used for direct comparison with measured profiles without the need for curve-fitting. Any discrepancies found immediately indicate where the most important knowledge is lacking. So far predicted chloride profiles coincide fairly well with measured ones, with the only exceptions being immersion tests with high chloride concentrations close to the exposed concrete surface. Possible improvements have been identified. The next steps in improving the scientific models should be: 1) a concentration-dependent diffusivity, $D_{Fl}(c)$, and 2) a saturation-dependent diffusivity, $D(S)$, where S is the degree of saturation.

In regard to the subject of the workshop, questions to be asked include: What is the required performance? What is meant by service life? Is reduced load-carrying capacity acceptable?

It was pointed out that many reports will issue from the three-year European project that is developing the Duracrete Chloride Penetration Model and will end soon.

2.4 CHLORIDE EXPOSED RC-STRUCTURES: CHLORIDE INGRESS AND LIFETIME PREDICTION BY THE HETEK MODEL

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In the design, construction, and maintenance of marine reinforced concrete structures different persons have different needs for information. The structural engineer needs an estimate in which the basic parameters of chloride ingress are based on a knowledge of the concrete, reinforcement, and the environment in order to plan and design marine structures. The entrepreneur (i.e., the contractor) needs the concrete to be accepted or rejected by pre-testing and trial casting before the construction of a marine structure starts. The building owner needs to be warned, on the basis of inspection and examination of the marine structure, in due time before corrosion starts,. The basic HETEK model can assist the structural engineer and the entrepreneur in obtaining the information they need from knowledge of the concrete composition, the rebar cover, and the environment, but owners of structures also need field data which differs depending on whether the structure is new or old. The HETEK model is based on observations at the Träslövsläge Marine Exposure Station in Sweden. It is the result of cooperation between the University of Gothenberg's Department of Materials and the Cementa Company in Sweden, and the AEC Laboratory and the Department of Mathematics of the Technical University of Denmark in Denmark. The model uses data obtained with the Scandinavian NT Build 443 test method. The main result of the work is a model for chloride ingress into concrete and prediction of the initiation period before corrosion of the steel reinforcement begins. The model applies to marine structures of reinforced concrete, as well as to reinforced concrete structures exposed to traffic splash containing chlorides. Inputs to the model are: the mixture proportions of the concrete; the class of chloride environment; and the thickness of the cover over the reinforcement bar in question. The outputs are the chloride profile at any time and the initiation period. Prediction of service lives is being addressed, but it is complicated by the need to know the criterion for initiation of corrosion (i.e., the threshold value of chloride in concrete) and the failure criterion, and the difficulty in predicting corrosion rates.

In marine environments chloride ingress has to be considered in a) submerged sections, b) sections in the splash zone, and c) sections exposed in the marine atmosphere above the splash zone. If proper care is taken, useful data on chloride distribution can be obtained from profile grinding of concrete cores. Chloride profiles can also be obtained from *insitu* measurements on drilled dust or by use of the CorroWatch* multiprobe [9] embedded in field

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